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13. ABSTRACT (Maximum 200 words)

In this report we summarize our research accomplishments supported by AASERT Grant F49620-92-J-0257, associated with our current grant F49620-95-1-0083. We have accomplished the following: (a) combining our research on inverse problems with our work on the development of multiresolution stochastic models in order to develop novel and very efficient methods for the fusion and inversion of heterogeneous and multiresolution sensor data; (b) developing a significant extension of the use of our scale-recursive multiresolution models for the modeling of spatial phenomena based both on a novel application of the concept of canonical correlations in statistics and on relaxing the relationship between variables in our multiresolution representations and the spatial variables they represent; (c) developing multiresolution models for SAR imagery and the use of these models as the basis for new and very effective likelihood feature for the discrimination of man-made objects and natural clutter; and (d) developing a new method for signal approximation and feature extraction known as high-resolution pursuit that produces stable and physically meaningful features and the application of this method to high-range resolution radar data.

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FinalTechnical Report for
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MULTIRESOLUTION SIGNAL AND SYSTEM ANALYSIS AND THE ANALYSIS AND CONTROL OF DISCRETE-EVENT DYNAMIC SYSTEMS

PRINCIPAL INVESTIGATOR: PROF. ALAN S. WILLSKY

for the period
1 September 1992 through 31 January 1996

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I. Description of research progress

In this report we summarize the research accomplishments supported by AFOSR AASERT Grant F49620-92-J-0257, associated with our previous AFOSR base research Grant F49620–92-J–0002 and our curerent grant F49620-95-1-0083. A complere summary of all of the research supported by our base grant can be found in the latest annual progress report for our current grant. We limit ourselves here to mentioning the research directly supported in part by the AASERT award. In particular, the funds provided by this AASERT award have been used over the lifetime of the project to fund research of three of the doctoral students working with Prof. Alan S. Willsky, the PI for this award. The students are Mr. Michael Daniel, Mr. William Irving, and Ms Seema Jaggi.

In particular the basic scope of our current research program is to carry out fundamental research in several interrelated areas: (a) the use of multiresolution methods in statistically optimal image analysis; (b) the development of a methodology for multiresolution data fusion and inversion with applications in several areas; (c) the development of computationally efficient and nearly-optimal estimation and prediction algorithms for extremely large-scale space-time data assimilation problems arising in remote sensing applications; and (d) the development of multiresolution and wavelet-based methods for multi-access and/or secure communications, for robust detection of abrupt changes in signals and systems, and for nonparametric system identification. Key features of this project are that (i) it blends together methods and issues in several fields, namely signal and image processing, systems and control, and large-scale computation; and (ii) each aspect of the proposed program contains both fundamental research in mathematical sciences *and* important applications of direct relevance to Air Force missions.

The specific research accomplishements of the students supported by our AASERT award are described in the publications listed in the next section and include the following:

(1) We have combined our research on inverse problems with our work on the development of multiresolution stochastic models (see the next topic). These models represent phenomena through a scale-recursive stochastic recursion in which the variables represented in the resulting pyramidal structure correspond to features of the phenomenon in question at a succession of resolutions. Thus, "point" measurements of the field at a coarse resolution in fact correspond to nonlocal measurements (e.g. inverse scattering or tomographic) of the fine-scale field. As a result, we obtain algorithms for the inversion

and fusion of multiresolution data that are orders of magnitude faster than previously developed methods and, in addition, directly produce both reconstructions at multiple resolutions as well as error variances for these reconstructions. The most significant new research results in this area have been in developing new methods for building multiscale models based on both a statistical description of the phenomenon to be estimated and a specification of the locations and nature of each of the available measurements. In particular each measurement is specified by a linear functional that captures the spatial averaging (if any) of the measurement. These new models have yielded impressive initial results and have also led to a new formalism for modeling and analyzing so-called 1/f processes and fractional Brownian motions. These results and their extension to allow for nonlinear measurements (through iterative relinearization) will be described in detail in the Ph.D. theses of Mr. Daniel (est. completion date of 9/96).

(2) The development of a significant extension of the use of our scale-recursive multiresolution models for the modeling of spatial phenomena. The specific theoretical contributions include the development of a theory of multiresolution stochastic realization building on the concept of canonical correlations that has proved so successful in the time-recursive modeling of time series and the development of what we have termed an "overlapped tree" modeling methodology in which we relax the relationship between variables represented at each node on our multiresolution tree and a specific region of physical space corresponding to the node. In particular, by using overlapped regions, we can develop models capable of capturing and reconstructing fields with any specified level of smoothness. Combining this concept with our canonical correlation-based stochastic realization methodology leads to a very powerful modeling framework that we have used with great success in a number of applications including the following. This modeling framework is described in the Ph.D. thesis of Dr. Irving which was completed in October 1995.

(3) The development of multiresolution models for SAR imagery and the use of these models as the basis of a new likelihood feature for the discrimination of man-made objects and natural clutter. The basic idea behind this work is the observation that the spatial distribution of scatterers is very different between targets and clutter and between different types of terrain. Consequently, if we form SAR images at a sequence of resolutions, the scale-to-scale variation in imagery should be very different for targets, clutter, and for different types of natural terrain, since the constructive and destructive interference among scatterers within resolution cells, as we vary the dimensions of these resolution cells, should have statistically distinct scale-to-scale characteristics resulting from the differences in scatterer distributions. The value of this concept was first proven

in the context of target-clutter discrimination. In particular, by using a variation of our multiresolution stochastic realization method that results in autoregressive models in scale for SAR imagery, we were able to identify statistically distinct models for targets and natural clutter using high-resolution SAR data provided by Lincoln Laboratory's ADTS SAR imaging system. Using these models, we developed a multiresolution likelihood ratio discriminant that is easily computed from the SAR imagery. Incorporating this discriminant into Lincoln's state-of-the-art SAR discrimination algorithm resulted in a factor of 6 reduction in false alarm rates. These results are also described in the Ph.D. thesis of Dr. Irving.

(4) The development of a new method for signal approximation and feature extraction known as high-resolution pursuit. This work is being carried out in direct collaboration with Prof. Stephane Mallat. In particular, one of the objectives of our work is to adapt the concept of matching pursuit developed by Prof. Mallat in order to extract a set of features that are both physically meaningful and robust to expected variations and noise in the observed signals and images. In particular, matching pursuit is a greedy algorithm for function fitting in which at each step we choose a function from a library of functions that provides the best fit to the residual signal at that step. Here "best" is in a least-squares sense (so that the calculation is simple) and the residual signal is the remainder signal after each successive best basis function is calculated. The main advantage of this method is speed--the sequence of "features", namely the basis functions chosen, can be calculated extremely efficiently. However, there are significant drawbacks to this method: (i) the method is greedy, as it looks at one basis element at a time with no regard to the interaction with other basis functions; (ii) the use of the least squares criterion means that the focus of the pursuit algorithm is on global fit--i.e., we wish to minimize the energy in the entire residual. In our work we have alleviated the disadvantages of matching pursuit without sacrificing its key advantage. In particular, we have developed a new criterion that trades off between global fit and local fit in choosing each of a succession of features and that has a very easily understood and intuitively appealing interpretation. This method involves only a modest increase in complexity over matching pursuit but leads to features which are much more clearly connected to physical features in data and which appear to have significant robustness to several types of noise, including additive noise as well as "spiky" noise, as one would expect in speckle-corrupted radar data. A paper describing the basic theory is nearing completion. In addition, we are currently applying this method to high-range resolution radar data provided by Rome Laboratory and simulated radar data that is to be generated using the X-Patch simulation tool developed at Wright Laboratory. We have had extremely

encouraging initial results in producing stable, physically meaningful features that are robust to these sources of noise and variability. This work will be documented in detail in the Ph.D. thesis of Ms Jaggi (estimated completion date of 9/96).

Publications

The publications listed below represent papers, reports, and theses supported in whole or in part by the Air Force Office of Scientific Research under Grant AFOSR–92-J–0257:

[1] M.M. Daniel and A.S. Willsky, "Efficient Implementation of Two-Dimensional Noncausal Filters," submitted to *IEEE Trans. on Circuits and Systems II*.

[2] P.W. Fieguth, W.W. Irving, and A.S. Willsky, "Overlapped Tree Models for Multiresolution Modeling and Estimation," submitted to *IEEE Trans. on Image Processing*.

[3] P.W. Fieguth, W.W. Irving, and A.S. Willsky, "Multiresolution Model Development for Overlapping Trees Via Canonical Correlation Analysis," accepted for the International Conference on Image Processing, October 1995.

[4] W Irving and A.S. Willsky, " A Canonical Correlations Approach to Multiscale Stochastic Realization," in preparation for submission.

[5] W.W. Irving, "Theory and Application of Multiresolution Stochastic Realization and Modeling for Random Fields," Ph.D. Thesis, October, 1995.

[6] W.W. Irving, L.M. Novak, and A.S. Willsky, "The Use of Multiresolution Models for the Discrimination of Targets and Clutter in SAR Imagery," SPIE Conference, Orlando, Florida, April 1995.

[7] W.W. Irving, A.S. Willsky, and L.M. Novak, "A Multiresolution Approach to Discriminating Targets from Clutter in SAR Imagery, submitted to *IEEE Trans. on Aerospace and Electronic Systems*.

[8] C. Fosgate, R. Chaney, H. Krim, W.W. Irving, and A.S. Willsky, "A Multiscale Approach to SAR Image Segmentation," submitted to the SPIE Conference, Orlando, Florida, April 1996.

[9] P.W. Fieguth, W.W. Irving, M.M. Daniel, C.H. Fosgate, M.K. Schneider, H. Krim, W.C. Karl, and A.S. Willsky, "Multiresolution Stochastic Models: Methodology and Applications in Remote Sensing, Image Processing, and Radar," Workshop on Image and Multidimensional Signal Processing, Belize City, Belize, March 1996.

[10] M.M. Daniel, A.S. Willsky, D.J. Rossi, and D. McLaughlin, "The Use of Multiresolution Stochastic Models for the Fusion and Inversion of Multiple Measurements for Reservoir Characterization," International Conference on Image Processing, Washington, D.C., October 1995.

[11] M.M. Daniel, "Multiresolution Methods in Fusion and Inversion of Measurements in Reservoir Characterization," Ph.D. thesis, in preparation.

[12] S. Jaggi, "Multiresolution Feature Extraction Using High-Resolution Pursuit and Morphology," Ph.D. thesis, in progress.

[13] S. Jaggi, W.C. Karl, H. Krim, and S. Mallat, A.S. Willsky, "Feature Extraction, Through High-Resolution Pursuit" in preparation for submission to the *Journal of Applied and Computational Harmonic Analysis*.

[14] S. Jaggi, W.C. Karl, H. Krim, and S. Mallat, A.S. Willsky, "Feature Extraction for Object Recognition Through High-Resolution Pursuit" International Conference on Image Processing, Washington, D.C., October 1995.

[15] M.M. Daniel, A.S. Willsky, D.B. McLaughlin, D.J. Rossi, "A Multiresolution Approach to Hydraulic Conductivity Estimation," SIAM Symposium on Inverse Problems: Geophysical Applications, December 1995.